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Observation of π – B Meson Charge-Flavor Correlations and Measurement of Time Dependent $B^0 \bar{B}^0$ Mixing in $p\bar{p}$ Collisions

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Observation of $\pi - B$ meson Charge-flavor Correlations and Measurement of Time Dependent $B^0\bar{B}^0$ Mixing in $p\bar{p}$ Collisions

The CDF Collaboration[1]

Abstract

We present evidence for charge correlations of B mesons with charged particles produced in $p\bar{p}$ collisions at 1.8 TeV. Such correlations are expected to arise from pions produced in the fragmentation chain and from B^{**} decays. We measure the efficiency and purity of this flavor tagging method for both charged and neutral B mesons. We apply these correlations to B mesons reconstructed in 110 pb^{-1} of data collected with the CDF detector at the Fermilab Tevatron Collider. B mesons are either partially reconstructed, using the semileptonic decays $B^0 \to \ell^+ D^{(*)-} X$ and $B^+ \to \ell^+ \bar{D}^0 X$, or fully reconstructed, using the decay modes $B^0 \to J/\psi K^{*0}$ and $B^+ \to J/\psi K^+$. Application of this new flavor tagging method to neutral B mesons yields a measurement of the frequency of the oscillation $B^0 \to \bar{B}^0$. We obtain $\Delta m_d = 0.446 \pm 0.057^{+0.034}_{-0.031}$.

[1]Contributed paper to the XXVIII International Conference on High Energy Physics, July 25-31, 1996, Warsaw, Poland.

1 Introduction

In this paper, we present evidence for the existence of charge correlations between B mesons and charged particles produced in the fragmentation of the b quarks[2]. Such correlations are expected [1] to arise from particles produced in the fragmentation chain and from decays of the $L = 1$ B mesons (the "B^{**}" mesons). Correlations between B-mesons and charged particles have already been reported by the LEP experiments [2]. This is the first observation of the same effect in hadronic collisions.

These charge correlations can be used to tag the flavor of B mesons at production time. We refer to this flavor tagging method as *Same Side Tagging* (SST) to distinguish it from other methods that rely on the second b-flavored hadron in the event. We measure the efficiency and purity of this flavor tagging method for both charged and neutral B mesons, and apply this flavor tag to neutral B mesons and observe a time-dependent flavor oscillation.

The data samples used correspond to 110 pb^{-1} of $p\bar{p}$ collisions recorded with the CDF detector at the Fermilab Tevatron Collider. B mesons are either partially reconstructed using the semileptonic decays $B^0 \rightarrow \ell^+ D^{(*)-} X$ and $B^+ \rightarrow \ell^+ \bar{D}^0 X$, or fully reconstructed using the decays $B^0 \rightarrow J/\psi K^{*0}$ and $B^+ \rightarrow J/\psi K^+$. The B meson proper decay time is reconstructed from the B decay length, which is measured using a precision Silicon Microstrip detector. The charge of the kaon in the $B \rightarrow J/\psi K^{(*)}$ decay and of the lepton ℓ in the partially reconstructed case signals the flavor of the B meson when it decays. The flavor at production is determined using B meson-charged pion correlations.

This paper is organized as follows: After a brief introduction to $B^0\bar{B}^0$ mixing and the Same Side Tagging technique, the CDF detector is described in section 2. In section 3 we apply same side tagging to partially reconstructed B mesons, where the statistics of the data sample are large enough to establish the charged particle-B meson correlation. We then use these correlations to perform a measurement of the $B^0 - \bar{B}^0$ mixing frequency, Δm_d. In section 4 we also use samples of fully reconstructed B mesons. These samples, while free from many systematic uncertainties inherent to partially reconstructed B samples, are statistically limited. We use the fully reconstructed B mesons only to extract the purity of the SST flavor tagging method. We find it to be consistent with the one extracted from the semileptonic decays. We conclude with section 5.

[2]In this paper, and unless otherwise noted, reference to a particular particle state implies the charge conjugate state also.

1.1 $B^0\bar{B}^0$ Mixing

For a beam initially pure in B^0 mesons (at $t = 0$), the numbers of B^0 and $\bar{B}^0$ mesons at proper time t, $N(t)_{B^0\to B^0}$ and $N(t)_{B^0\to \bar{B}^0}$, respectively, are given by:

$$N(t)_{B^0\to B^0} = \frac{1}{2\tau}e^{-t/\tau}(1 + \cos\Delta m_d t) \tag{1}$$

$$N(t)_{B^0\to B^0} = \frac{1}{2\tau}e^{-t/\tau}(1 - \cos\Delta m_d t), \tag{2}$$

where τ is the lifetime of the B^0 meson and Δm_d is the B^0-$\bar{B}^0$ mass difference. Experimentally, the flavor of the B meson is determined at the time of its decay from the observed decay products. The flavor at production time can be determined in various ways, employing either the second b-flavored hadron in the event, or the charge correlations with particles produced in association with the B meson. In an experiment with no background, perfect lifetime reconstruction and perfect flavor tagging, the mixing frequency, Δm_d, can be determined from the asymmetry $A(t)$ defined as

$$A(t) \equiv \frac{N(t)_{B^0\to B^0} - N(t)_{B^0\to B^0}}{N(t)_{B^0\to B^0} + N(t)_{B^0\to B^0}} = \cos\Delta m_d t \tag{3}$$

If the probability that the flavor tag correctly identifies the B^0 flavor at production is P, then the amplitude of the observed asymmetry, $A_m(t)$, is reduced by a factor $2P - 1$:

$$A_m(t) = (2P - 1)\cdot\cos\Delta m_d t \tag{4}$$

The oscillation amplitude of the asymmetry is thus decreased by the "dilution" factor $D = 2P - 1$, i.e. $A_m = DA$. The uncertainty on the measurement of the asymmetry A from a sample of N events is given by

$$\sigma_A^2 = (1 - A^2D^2)/N\varepsilon D^2 \simeq 1/N\varepsilon D^2. \tag{5}$$

where ε is the efficiency of the flavor tagging method employed. The quantity εD^2 is the *effective tagging efficiency* of the tagging method.

In the study of same side tagging using partially reconstructed B mesons, we determine the dilution, D, and the oscillation frequency, $Deltam_d$, simultaneously, by fitting the observed asymmetry in the data to the expected oscillation curve.

1.2 Same Side Tagging

The flavor of a B meson at production time can be inferred from the second b-flavored hadron in the event. Various techniques have already been used to determine the flavor of this second hadron: examples are lepton-tagging or jet charge-tagging. We refer to such methods, which employ the "other" b-flavored hadron in the event, as *opposite side tagging* (OST) methods. Monte Carlo simulations indicate that in a hadron collider detector with central rapidity coverage such as CDF, once one B meson is produced in the central rapidity region, the second b-flavored hadron is also produced in the central region of the detector only $\sim 40\%$ of the time. For lepton tagging, there is the additional loss of efficiency arising from the branching ratio $b \to \ell$. For jet-charge tagging, the purity of the flavor-tag decision is reduced by the presence of charged tracks from the proton-antiproton remnants. Finally, flavor tagging based on OST suffers from the inevitable dilution arising from mixing of the second b-flavored hadron.

In contrast, *same side tagging* (SST) ignores the second b-flavored hadron and, instead, considers correlations of charged particles produced along with the B meson of interest. These correlations arise from either the tracks originating from the fragmentation of a b quark into a B meson or from decays of higher B resonances such as B^{**}. Figure 1 displays possible fragmentation paths for a $\bar{b}$ quark, assuming a naive view of string fragmentation. If the $\bar{b}$ quark combines with a u quark to form a B^+ meson, then the remaining $\bar{u}$ quark may combine with a d quark to form a π^-. Similarly, if the $\bar{b}$ quark fragments to form a B^0 meson, the correlated pion would be a π^+. Another possible source of correlated pions are B^{**} decays like $B^{**0} \to B^{(*)+}\pi^-$ or $B^{**+} \to B^{(*)0}\pi^+$. The correlations here are the same as for pions produced in fragmentation. In this analysis no attempt is made to differentiate the sources of correlated pions.

In this simple picture of fragmentation, we expect charged B mesons to display a higher degree of correlation with charged particles than neutral B mesons. This is due to the production of strange quarks in the fragmentation process. The resulting strange particle would be a K^- for a B^+ and a $\bar{K}^0$ for a B^0. As a result of these considerations, the dilution for B^+ is expected to be higher than the dilution for B^0.

The efficiency of the SST algorithm is given by

$$\varepsilon = \frac{N_{RS} + N_{WS}}{N_T} \tag{6}$$

where N_{RS} (N_{WS}) are the number of events tagged with the right (wrong) B flavor and N_T

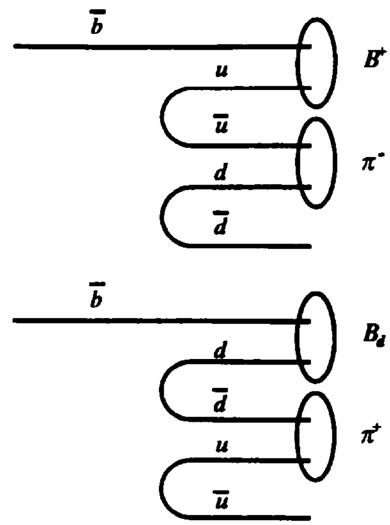

Figure 1: Possible fragmentation paths for a $\bar{b}$ quark, assuming a naive view of string fragmentation.

is the total number of B mesons in the data sample. The dilution of the SST is given by

$$D = \frac{N_{RS} - N_{WS}}{N_{RS} + N_{WS}}. \tag{7}$$

2 The CDF Detector

The CDF detector is described in detail elsewhere [3]. We describe here only the detector features most relevant to this analysis. Two devices inside the 1.4 T solenoid are used for the tracking of charged particles: the silicon vertex detector (SVX) and the central tracking chamber (CTC). The SVX consists of four layers of silicon microstrip detectors and provides spatial measurements in the r-φ plane. At CDF, ϕ is the azimuthal angle, θ is the polar angle measured from the proton direction, and r is the radius from the beam axis (z-axis). Combined, the CTC and SVX give a track impact parameter resolution of about $(13 + 40/p_t)$ μm [4], where p_t is the transverse momentum of the track in GeV/c. The geometric acceptance of the SVX is $\sim$ 60% as it extends to only $\pm$ 25 cm from the nominal interaction point whereas the Tevatron beam has an RMS width of $\sim$ 30 cm along the beam (z) direction. The transverse profile of the beam is circular and has an RMS of $\sim$ 35 μm. The CTC is a cylindrical drift chamber containing 84 layers grouped into

8 alternating superlayers of axial and stereo wires. It covers the pseudorapidity interval $|\eta| < 1.1$, where $\eta = -\ln[\tan(\theta/2)]$. The p_t resolution of the CTC combined with the SVX is $\delta(p_t)/p_t = ((0.0066)^2 + (0.0009 p_t)^2)^{1/2}$. Outside the solenoid are electromagnetic (CEM) and hadronic (CHA) calorimeters ($|\eta| < 1.1$) that employ a projective tower geometry with a segmentation of $\Delta\eta \times \Delta\varphi \sim 0.1 \times 15°$. A layer of proportional wire chambers (CES) is located near shower maximum in the CEM and provides a measurement of electromagnetic shower profiles in both the φ and z directions. Two muon subsystems in the central region are used, the central muon chambers (CMU) and the central upgrade muon chambers (CMP), with total coverage of 80% for $|\eta| \leq 0.6$. The CMP chambers are located behind 8 interaction lengths of material.

3 Study of Same Side Tagging Using Partially Reconstructed B Mesons

3.1 B Candidate Selection

For the reconstruction of the neutral B mesons, we use the decay modes $B^0 \to \nu\ell^+D^-$, with $D^- \to K^+\pi^-\pi^-$, and $B^0 \to \nu\ell^+D^{*-}$, with $D^{*-} \to \bar{D}^0\pi_s^-$, followed by $\bar{D}^0$ decaying to $K^+\pi^-$, $K^+\pi^-\pi^+\pi^-$, or $K^+\pi^-\pi^0$. For the B^+, we use only one decay mode, $B^+ \to \nu\ell^+\bar{D}^0$, with $\bar{D}^0 \to K^+\pi^-$, where the $\bar{D}^0$ is required to not form a D^{*-} candidate with another π candidate. In total, there are five decay sequences, four for B^0 and one for B^+.

We begin the reconstruction with a data set collected using inclusive single electron and muon triggers. The E_T threshold for the principal single electron trigger was 8 GeV, where $E_T \equiv E\sin\theta$ and E is the electromagnetic energy measured in the calorimeter. The single muon trigger required a $p_t > 7.5$ GeV/c track in the CTC with matched track segments in both the CMU and CMP systems. The identification of electrons and muons is described in references [8] and [9]. The search for D meson candidates is performed in a cone of unit radius in η-ϕ space around the lepton. To ensure the precise reconstruction of the B meson decay position, all charged particle trajectories are required to include information from the silicon microstrip detector. To decrease combinatorial background, the decay products from the weakly decaying D mesons are required to have impact parameters that are significantly displaced from the B production point. Furthermore, the kaon from the D decay and the lepton are required to have the same charge.

The mass distributions of the four modes with fully reconstructed D mesons is shown in Fig. 2, while the mass distribution of $\Delta m = m(K\pi\pi_s) - m(K\pi)$ for the mode with $D^{*-} \rightarrow \bar{D}^0\pi_s^-$, with $\bar{D}^0 \rightarrow K^+\pi^-\pi^0$ (the π^0 is not reconstructed) is displayed in Fig. 3.

3.2 B Meson Proper Decay Time and Resolution Effects

The silicon microstip detector only reconstructs trajectories in the plane perpendicular to the beam line. We therefore measure the projection L_{xy}^B in this plane of the distance between the B production point (primary vertex) and the B decay point. The B hadron decay vertex is reconstructed by first determining the D vertex, and then intersecting the D candidate with the lepton (and the π_s from the D^* if present) to form the B vertex. We apply requirements on the χ^2 of the fit to a secondary vertex to reduce combinatorial background. An example of the resolution of the reconstructed L_{xy}^B from a Monte Carlo simulation can be found in Fig. 4a.

To determine the proper decay time $c\tau$, the transverse momentum of the B, p_t^B, has to be known. Since the B is not fully reconstructed, p_t^B is approximated with $p_t^{lD} = |\vec{p}_t(\ell) + \vec{p}_t(D)|$:

$$c\tau = L_{xy}^B \frac{m_B}{p_t^B} = L_{xy}^B \frac{m_B}{p_t^{lD}} K \tag{8}$$

where K is a factor that corrects on average for any missing momentum (*e.g.* from the neutrino). This average factor is determined from Monte Carlo simulation of the decay in question. The distribution of $K = p_t^{lD}/p_t^B$, is shown in Fig. 4b. This distribution has a mean of $\approx 86\%$ and an RMS of $\approx 11\%$.

3.3 Applying Same-Side Tagging to Partially Reconstructed B Mesons

To study the correlation between the flavor of the B meson and the charge particles produced in association with it, we consider all tracks that are within the η-ϕ cone of radius 0.7 centered around the direction of the B meson. Since the B meson is only partially reconstructed, we approximate this direction with the momentum sum of the lepton and charm hadron.

The tracks considered should be consistent with the hypothesis that they originate from the fragmentation chain or the decay of B^{**} mesons, i.e. that they originate from the primary vertex of the event. All tracks are therefore required to satisfy the requirement $d_0/\sigma_d < 3$ where d_0 is the distance of closest approach of the track trajectory to the estimated B

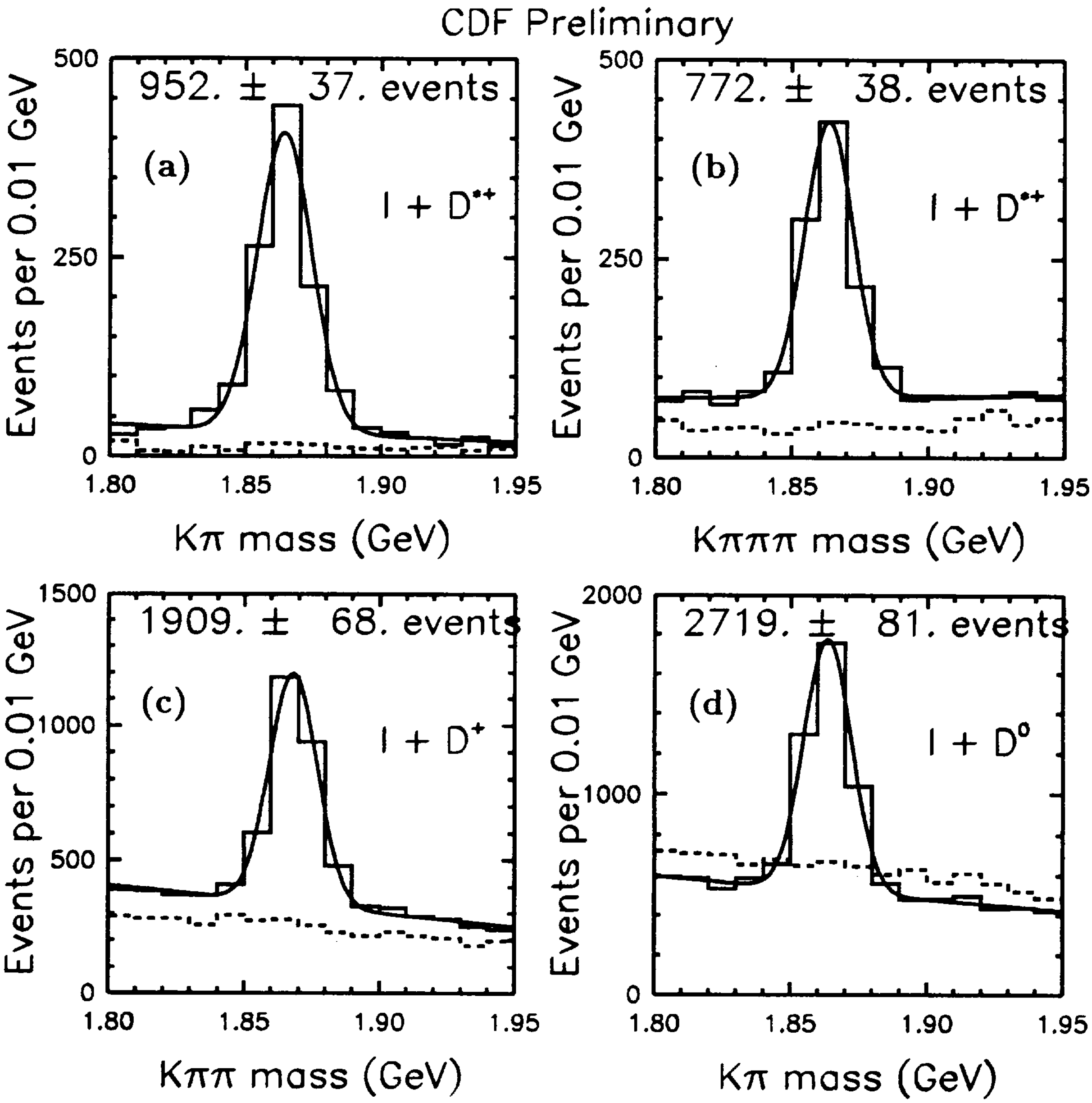

Figure 2: Mass distributions of the four modes with fully reconstructed D mesons: $D^{*-} \to \bar{D}^0\pi_s^-$ followed by $\bar{D}^0$ decaying to (a) $K^+\pi^-$ and (b) $K^+\pi^-\pi^+\pi^-$. Displayed in (c) is $D^- \to K^+\pi^-\pi^-$, and (d) $\bar{D}^0 \to K^+\pi^-$.

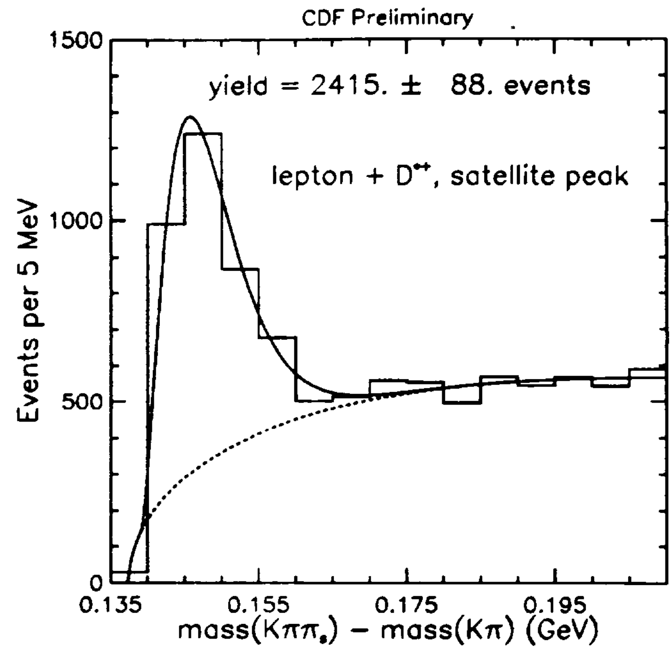

Figure 3: Mass distribution of $\Delta m = m(K\pi\pi_s) - m(K\pi)$ for the mode with $D^{*-} \rightarrow \bar{D}^0\pi_s^-$, with $\bar{D}^0 \rightarrow K^+\pi^-\pi^0$ (the π^0 is not reconstructed).

production position, and σ_d is the estimated error on this quantity. Finally, to ensure equal reconstruction efficiencies for positive and negative tracks, all tracks are required to have transverse momentum $p_t > 0.4$ GeV/c.

String fragmentation models indicate that the velocity of the fragmentation particles, that we seek for our tag, is close to the velocity of the B meson. Similarly, pions from B^{**} decays should also have a velocity close to the velocity of the B meson. In particular, the relative-transverse momentum ($p_t^{\rm rel}$) of the particle with respect to the combined momentum of B- plus particle momentum, should be small. Of the candidate tracks, we select as the tag the track that has the minimum component of momentum $p_t^{\rm rel}$ orthogonal to the momentum sum of that track, the lepton, and the D meson.

A B candidate is tagged, if there is at least one track that satisfies the selection requirements for a tag candidate. The ratio of the number of tagged B candidates to the total number of B candidates is defined as the tagging efficiency. The distributions of the tagging efficiencies as a function of the proper decay time of the B meson are displayed in Figure 5. The average efficiency is $\approx 72\%$.

The charge of the tag track determines the flavor of the B at production; we compare

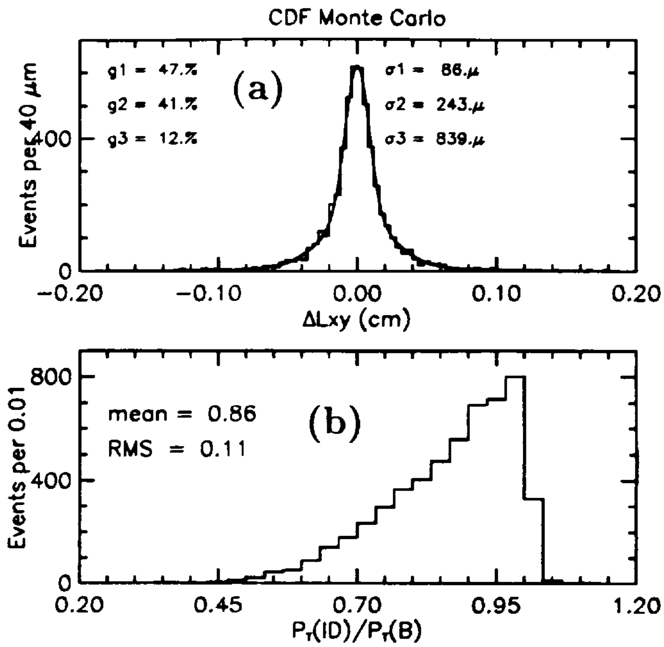

Figure 4: Examples of (a) the resolution in L_{xy}, and (b) the distribution of the factor $K = p_t^{lD}/p_t^B$ obtained from a Monte Carlo simulation.

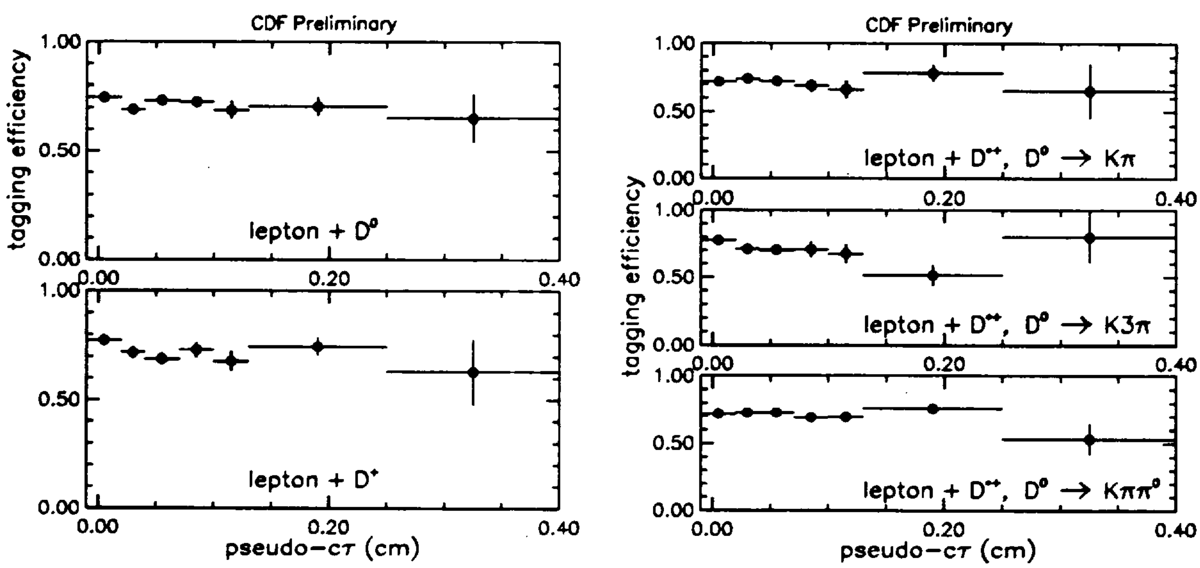

Figure 5: Tagging efficiencies versus $c\tau$ for all five $D^{(*)}\ell$ decay modes.

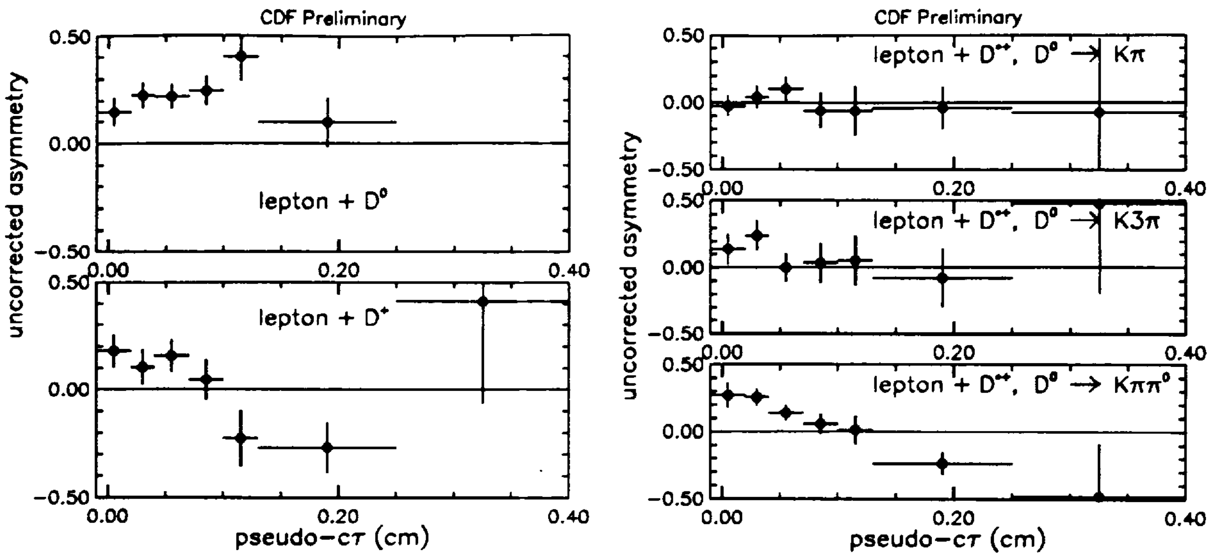

Figure 6: Raw asymetries versus $c\tau$ for all five $D^{(*)}\ell$ decay modes.

this charge to the charge of the lepton from the B to classify the B candidate as unmixed (RS) or mixed (WS).

For each of the five decay sequences, we classify the candidates into seven bins in corrected proper lifetime $c\tau$. We measure the asymmetry in each bin, by fitting simultaneously the signals from the mass distributions for candidates tagged as unmixed and candidates tagged as mixed. The resulting asymmetries have the combinatorial background subtracted. The resulting raw asymmetries are shown in Fig. 6a) and 6b). The reason for referring to them as *raw* or uncorrected is explained in the following section.

3.4 Correcting the Dilutions for the Sample Composition

To obtain results on the same-side flavor tagging effectiveness and on Δm_d, we need to combine our five raw asymmetries into an asymmetry for B^0 ($\mathcal{A}_0(c\tau)$) and an asymmetry for B^+ ($\mathcal{A}_+(c\tau)$). We expect $\mathcal{A}_0(c\tau)$ to display a cosine dependence on $c\tau$ and $\mathcal{A}_+(c\tau)$ to be flat.

The signatures $\ell^+ + D^{*-}$ and $\ell^+ + D^-$ are not pure signals of B^0 decays: there is some contamination from B^+. Similarily, there is some contamination of B^0 decays in the B^+ sample from $\ell^+ + \bar{D}^0$. This cross-contamination arises from two sources. First, if the soft pion π_s^- from the D^{*-} decay is not identified, then the decay sequence $B^0 \to \nu\ell^+ D^{*-}$ will be reconstructed as $\ell^+\bar{D}^0$, that is, as a "B^+." Since the efficiency for reconstructing the soft pion, $\epsilon(\pi_s)$, is high ($\approx 88\%$), this is not a serious source of cross-contamination.

A more serious source of cross-contamination arises from semileptonic B meson decays involving P-wave D resonances (the so-called D^{**}'s) as well as nonresonant $D\pi$ production. For example, the decay sequence $B^0 \rightarrow \nu\ell^+D^{**-}$, followed by $D^{**-} \rightarrow \bar{D}^0\pi^-_{**}$, may be reconstructed as $\ell^+\bar{D}^0$; again, a B^0 is misclassified as a "B^+". We quantify the level of this source of cross-contamination with the parameter f^{**}, which is the ratio of the branching fraction $BR(B \rightarrow \nu\ell D^{**})$ to the inclusive semileptonic B branching fraction:

$$f^{**} \equiv \frac{BR(B \rightarrow \bar{\nu}\ell D^{**})}{BR(B \rightarrow \bar{\nu}\ell X)}. \tag{9}$$

The value of f^{**} that we use is based on the measurement $f^{**} = (36 \pm 12)\%$ [10]. Monte Carlo simulations of the trigger and D meson reconstruction requirements indicate that the relative fraction of $B \rightarrow \bar{\nu}\ell D^{**}$ decays in the data samples considered here is reduced. This results in an effective value of $f^{**} = (21 \pm 7)\%$ for this analysis.

In addition to correcting the observed numbers of B^0 and B^+ decays, we must also correct the observed asymmetries. This correction is necessary, because a B^+ is associated with a π^-, but an unmixed B^0 is associated with a π^+: the observed asymmetries are reduced by cross-contamination. When the cross-contamination is due to D^{**} decays there is an even more insidious problem: the $\pi^\pm_{**}$ from the D^{**} may be selected as the tag by mistake. This error always results in the expected charge correlation between the lepton and the tag. We quantify this effect with the parameter ξ, defined as a probability of selecting the π_{**} as a tag in a tagged event where the π_{**} was produced:

$$\xi \equiv \frac{N(\text{candidate tagged with } \pi_{**})}{N(\text{candidate is taggable and } \pi_{**} \text{ was produced})}. \tag{10}$$

The requirement $d_0/\sigma_d < 3$ (see section 3.3) was introduced to reduce this effect: the π_{**} originates from the B meson decay point, but the appropriate tagging track originates from the B meson production point.

3.5 Fitting the Oscillation

The corrected asymmetries $\mathcal{A}_+$ and $\mathcal{A}_0$ are shown in Figure 7. These asymmetries have the combinatorial background subtracted and have been corrected for the sample composition and the effect of π_{**}, hence they represent *the pure signal.*

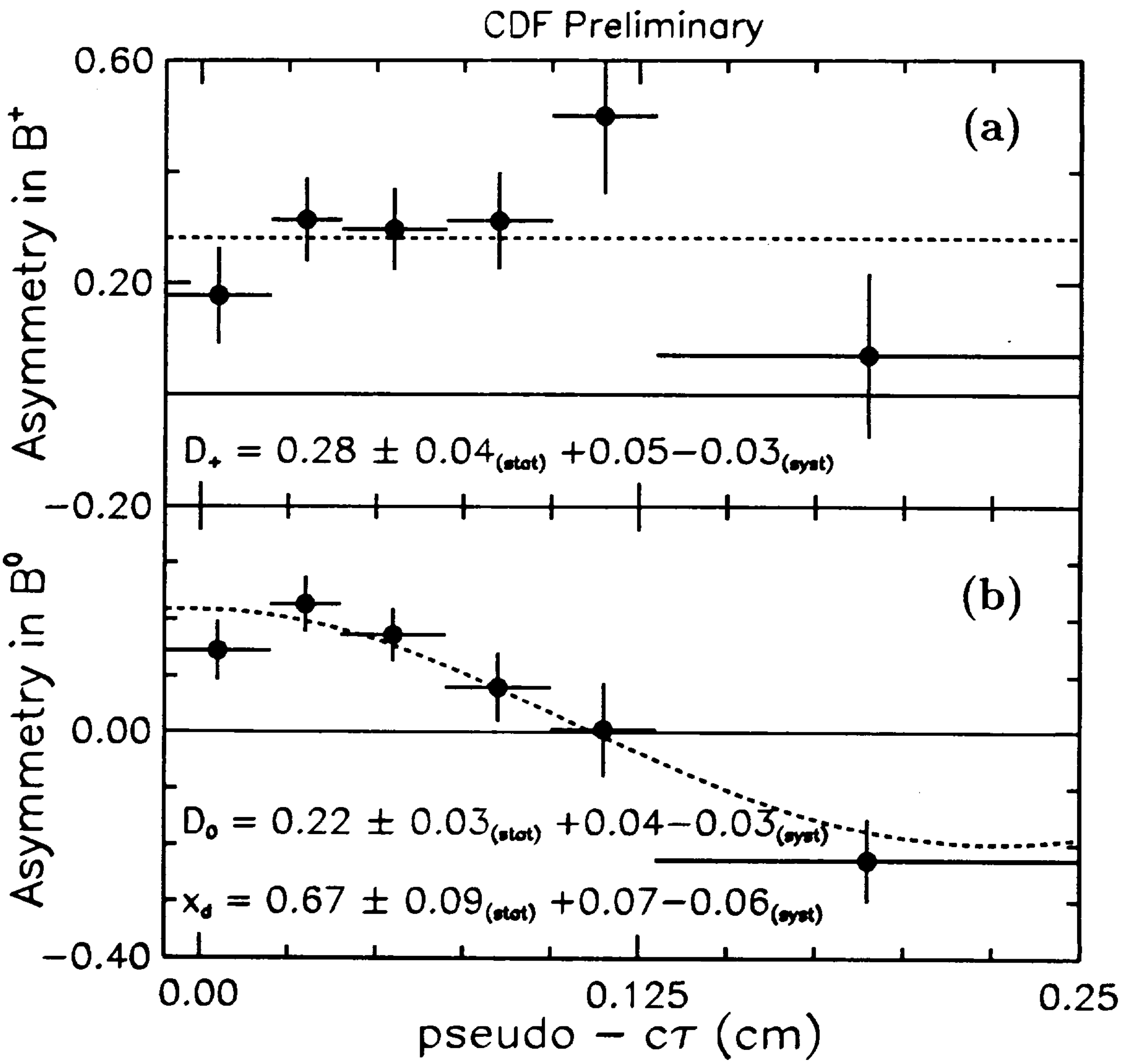

Figure 7: Corrected asymmetries (a) $\mathcal{A}_+$ for charged B mesons, and (b) $\mathcal{A}_0$ for neutral B candidates versus $c\tau$.

Source	Central value	Variation	$\Delta(\Delta m_d)$.	ΔD_0	ΔD_+
$\epsilon(\pi_s)$	0.88	$+0.12$ -0.21	$+0.003$ -0.005	$+0.006$ -0.004	$+0.039$ -0.022
eff. P_V	0.61	$+0.39$ -0.41	$+0.018$ -0.005	$+0.011$ -0.019	$+0.001$ -0.009
f^*/f	3.7	$+4.5$ -2.9	$+0.000$ -0.001	$+0.002$ -0.000	0.000 -0.001
eff. f^{**}	0.21	±0.08	$+0.028$ -0.029	$+0.034$ -0.025	$+0.033$ -0.025
ξ_{norm}	0.69	±0.17	±0.002	±0.005	±0.004
B^0 Lifetime	450μm	$\pm33\mu$m	$+0.002$ -0.004	0.0	–
Resolutions	–	–	$+0.006$ -0.005	±0.001	–
Total	–	–	$+0.034$ -0.031	$+0.04$ -0.03	$+0.05$ -0.03

Table 1: Compilation of the systematic errors.

Because charged B mesons do not mix, $\mathcal{A}_+ = \mathcal{A}_+(c\tau)$ is expected to be a constant (denoted by D_+ below), while $\mathcal{A}_0 = \mathcal{A}_0(c\tau)$ is expected to follow the cosine law from equation (4). A χ^2 fit to a flat line yields $D_+ = 0.28 \pm 0.04_{stat}$. In the case of $\mathcal{A}_0$, we have to take into account the imperfect $c\tau$ resolution. Every $c\tau$ bin has a contribution from events that originated from the neighboring bins. The fit to the corrected asymmetry for neutral B mesons is shown in Fig. 7b. The result is $\Delta m_d = 0.446 \pm 0.057_{stat}$. The dilution is $D_0 = 0.22 \pm 0.03_{stat}$.

The dominant systematic error is the uncertainty on the sample composition. The systematic errors are summarized in the Table 1.

3.6 Δm_d: Final Results

We have applied a same-side flavor tag to a sample of $B \to \ell D^{(*)}$ decays. The observed asymmetry for the charged B's, $\mathcal{A}_+$ is constant in $c\tau$, while the observed asymmetry for the neutral B's, $\mathcal{A}_0$ shows the expected oscillatory behavior. The fit of $\mathcal{A}_+(c\tau)$ to a straight line yields:

$$D_+ = 0.28 \pm 0.04_{stat} + \{^{+0.05}_{-0.03}\}_{syst}.$$

The fit of $\mathcal{A}_0(c\tau)$ to a cosine convoluted with the resolution function for observed proper time yields :

$$D_0 = 0.22 \pm 0.03_{stat} + \{^{+0.04}_{-0.03}\}_{syst}$$

and

$$\Delta m_d = 0.446 \pm 0.057^{+0.034}_{-0.031}$$

. Assuming a B^0 lifetime of $c\tau = 450 \pm 33\mu$m, the mixing parameter $x_d = \Delta m_d \tau$ is measured to be

$$x_d = 0.67 \pm 0.09_{stat} + \{^{+0.07}_{-0.06}\}_{syst}.$$

The observed effectived tagging efficiencies are

$$\varepsilon D_+^2 = (5.7 \pm 1.5_{stat}\{^{+2.0}_{-1.2}\}_{syst})\% \text{ and } \varepsilon D_0^2 = (3.4 \pm 1.0_{stat}\{^{+1.2}_{-0.9}\}_{syst})\%.$$

4 Study of Same Side Tagging Using Fully Reconstructed B Mesons

4.1 The Data Sample of Completely Reconstructed B mesons

The data sample used for the study of same side tagging with completely reconstructed $B \to J/\psi K^{(*)}$ mesons is 110 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. CDF uses a three-level trigger system to select dimuon events, which are the source of a high purity sample of $J/\psi \to \mu^+\mu^-$ used for this study. At Level 1 the relevant trigger for this analysis requires the presence of 2 charged tracks in the central muon chambers, which cover the pseudorapidity range $|\eta| < 0.6$. The efficiency of finding a muon at Level 1 rises from 30% at transverse momentum $p_t = 1.5$ GeV/c to 93% for $p_t > 3$ GeV/c. Level 2 requires that both muon tracks match a charged track in the Central Tracking Chamber found with the Central Fast Track (CFT) processor [5]. The efficiency of finding a track in the CFT rises from 50% at 1.95 GeV/c to 97% for $p_t > 2.4$ GeV/c. The Level 3 software trigger requires the presence of two oppositely charged muon candidates with invariant mass between 2.8 and 3.4 GeV/c^2 [6].

420,000 J/ψ candidates are reconstructed from the dimuon data, as displayed in Figure 8. B candidates are recontructed by combining a J/ψ candidate either with one track (assumed to be a K^+), or with two oppositely charged tracks (assumed to be a K^+ or π^-) forming a K^{*0} candidate. Combinations where the $K\pi$ mass is more than 80 MeV/c^2 from the world average K^{*0} mass [7] are rejected. Candidates with $p_t(K^+) < 0.8$ GeV/c, $p_t(\pi^+) < 0.5$ GeV/c, and $p_t(B) < 5$ GeV/c are also rejected. To improve the mass resolution all tracks are vertex constrained and the dimuon mass is constrained to the world average J/ψ mass [7]. As in the previous analysis, we use the decay distance, L^B_{xy}, measured in the transverse plane,

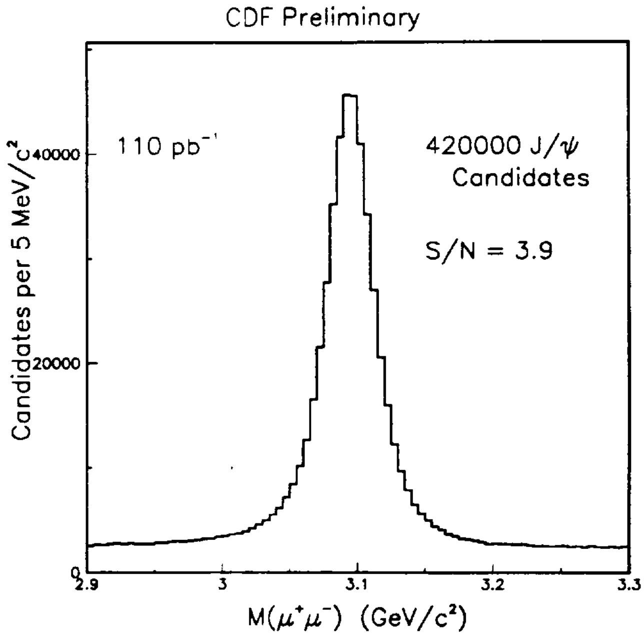

Figure 8: Invariant mass distribution of the dimuon $J/\psi \rightarrow \mu^+\mu^-$ candidates.

between the B production point (primary vertex) and the B decay point. We also require the proper lifetime of the B candidates to be $c\tau > 50$ μm, where $c\tau = L^B_{xy} \cdot m_B/p^B_t$. The transverse momentum of the B meson, p^B_t, is calculated directly from the B decay products, with no correction factor from Monte Carlo, as the B meson is fully reconstructed. As shown in Figure 9a ≈ 690 $B^+ \rightarrow J/\psi K^+$ candidates are found, while ≈ 320 $B^0 \rightarrow J/\psi K^{*0}$ candidates with $K^{*0} \rightarrow K^+\pi^-$ are reconstructed as can be seen in Figure 9b.

4.2 Same Side Jet Charge Tagging

To tag the flavor of the B meson using the SST technique, we employ two different algorithms. The first algorithm, just as in the partially reconstructed B meson analysis, a single track is selected. It is the track that has the minimum component of momentum p^{rel}_t orthogonal to the momentum of that track and the B candidate itself. We measure time-integrated asymmetries of $D_+ = 0.28 \pm 0.08$ and $D_0 = 0.11 \pm 0.11$ for the charged and neutral B mesons respectively. Including the corrections described in section 4.3, the true dilution for B^0 mesons is $D_0 = 0.20 \pm 0.20$.

The second algorithm utilizes all the charged particle tracks reconstructed around the B

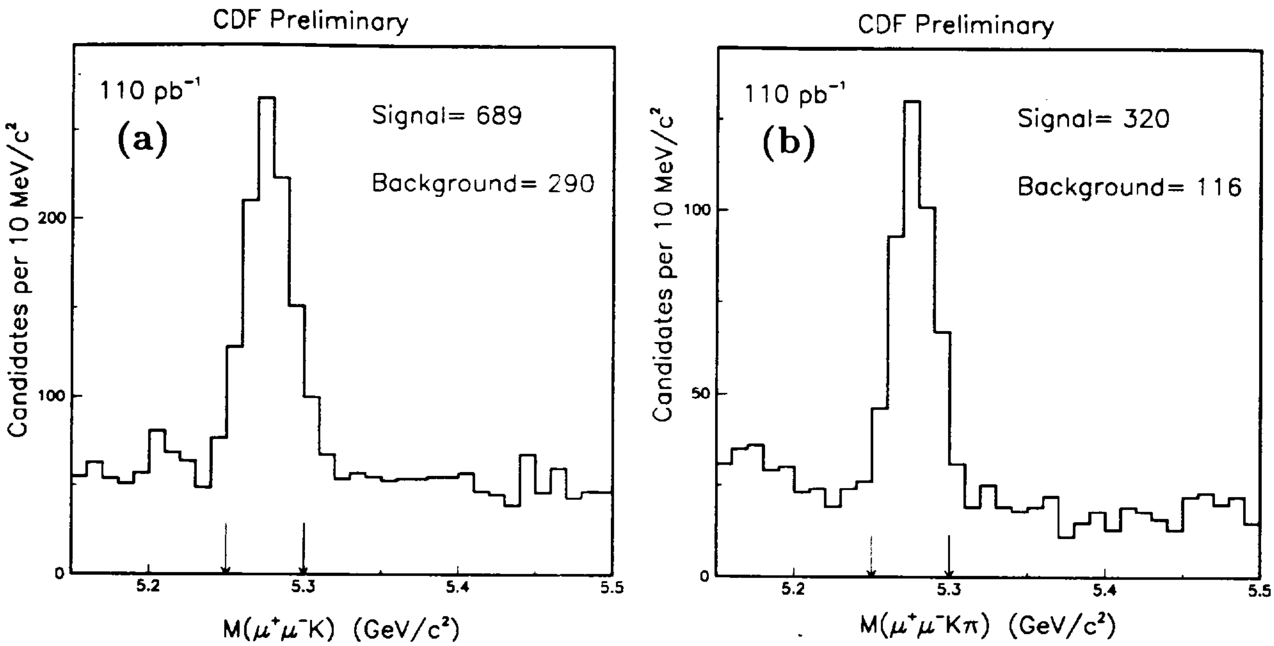

Figure 9: Invariant mass distribution for (a) $B^+ \to J/\psi K^+$ candidates and (b) $B^0 \to J/\psi K^{*0}$ candidates with $K^{*0} \to K^+\pi^-$.

candidate. This second algorithm has not been used in the case of partially reconstructed B mesons, because decay products from the B candidate itself (e.g. from D^{**} decays) could be included in the jet charge by mistake.

We adapt the technique of jet-charge tagging to same-side tagging by forming the normalized, weighted sum of the charges of tracks near a B meson:

$$Q_{SST} = \frac{\sum_i q_i w_i}{\sum_i w_i}. \tag{11}$$

Here, q_i is $+1$ for right-sign tracks, -1 for wrong-sign tracks, and w_i is the tagging weight.

Tracks contained in a cone in η-ϕ space of radius 0.7 centered around the B candidate excluding the tracks forming the B candidate are used. The transverse momentum of the tracks with respect to the beam axis (p_t) is required to exceed 0.7 GeV/c. In addition, all tagging track candidates are required to be consistent with originating from the B production point.

The following weighting function is selected:

$$w_i = \exp\left\{-\frac{1}{2}\left(\frac{p_t^{\rm rel} - 0.46}{0.3}\right)^2\right\} \tag{12}$$

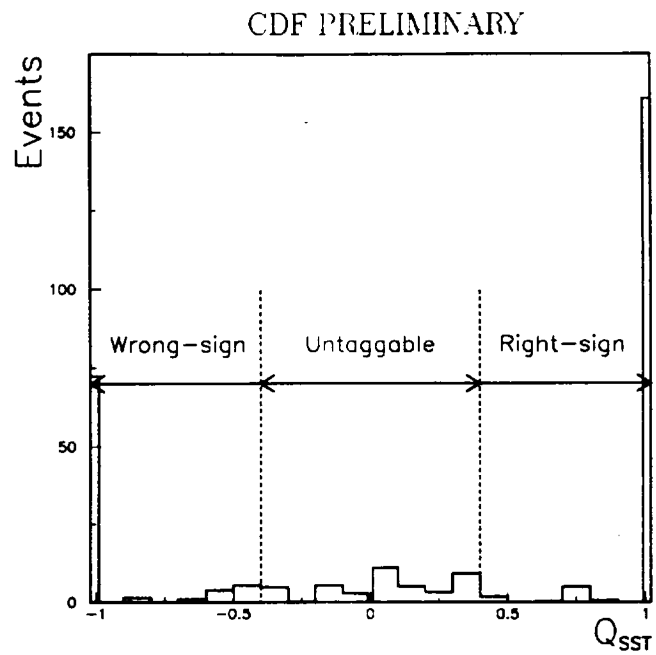

Figure 10: Distribution of Q_{SST} as described in the text.

The coefficients 0.46 and 0.3 have been determined empirically from Monte Carlo studies.

To finally apply our tagging method, a value X is chosen, such that candidates with $Q_{SST} > X$ are considered right sign, those candidates with $Q_{SST} < -X$ are considered wrong sign, and the remaining candidates are considered to be untaggable. We choose $X = 0.4$, which maximizes εD^2. The distribution of Q_{SST} can be seen in Figure 10.

4.3 B^0 Dilution Corrections

Two effects are expected to affect the dilutions measured for neutral B mesons. First, due to the limited statistics, only a time-integrated measurement of the asymmetry (see equation (4)) is meaningful. This results in a number of wrong correlations arising from $B^0\bar{B}^0$ mixing. Since the fraction of B^0 candidates that mixed is known from the measured mixing parameter x_d [7], we can correct for this effect. Second, we identify the B^0 flavor at decay from the charge of the kaon: B^0 with a K^+, and $\bar{B}^0$ with a K^-. In this analysis, we do not differentiate between a kaon and a pion directly. Instead we take the $K\pi$ mass combination that yields a K^{*0} mass closest to the nominal value. Monte Carlo simulation of $B^0 \to J/\psi K^{*0}$ decays indicates that this procedure results in the correct K-π assignment in 95% of the decays. We correct for these misidentifications, as well.

Once the dilution of our samples are determined from the number of RS and WS tags, the observed dilution D_{obs} for neutral B mesons is corrected for B^0 mixing and K-π misassignment as follows:

$$D = D_{obs} \times C_S \times C_M. \tag{13}$$

Here, C_S is the correction for incorrect K-π assignment in forming a K^{*0} candidate, and C_M is the correction due to $B\bar{B}$ mixing.

A comparison with Monte-Carlo is used to predict how often the B^0 meson is misidentified, by swapping the K and π. This probability is $P_S = (5.3 \pm 0.6)\%$, and the correction yields $C_S = 1.12 \pm 0.02$.

If our B selection criteria were independent of the proper decay time t of the B^0 meson, the correction due to $B\bar{B}$ mixing would be $C_M = 1/(1 - 2\chi_d) = 1.45$, where χ_d is the time integrated B^0 mixing parameter [7]. The selection criteria like the cut $c\tau > 50\mu$m, however, favour B candidates with larger t. This enhances the fraction of mixed candidates in the sample, and results in a larger correction: $C_M = 1.72 \pm 0.16$. The uncertainty in this correction comes from the uncertainty in the B^0 lifetime and the B^0 mixing parameter χ_d taken from [7]. The total correction is: $C = C_S \times C_M = 1.93 \pm 0.18$.

4.4 Final Results

The final results for the efficiency ε, dilution D, and effective tagging efficiency εD^2 are summarized in Table 2. For comparison, this table includes the predictions of the PYTHIA Monte Carlo for two cases: one in which B^{**} states have been included (at a production level of about 30%) and the second with no B^{**} states in the fragmentation chain. The Monte Carlo does not adequately reproduce the underlying event in the $p\bar{p}$ collision: the number of tagging tracks around the B is lower in the Monte Carlo than in the data. Therefore the MC shows a lower efficiency. On the other hand, the dilutions in the Monte Carlo agree very well with the dilutions measured in the data.

The dilution in the charged sample is measured to be (33±8)% with an εD^2 of (4.0±1.9)%. The result in the neutral case is limited by statistics. The uncorrected dilution is (10±10)%; applying the corrections described in the previous Section, we find $D = (19 \pm 19 \pm 2)\%$ and $\varepsilon D^2 = (1.5 \pm 3.0 \pm 0.3)\%$. The Monte Carlo reproduces the measured dilution and εD^2 of the charged B mesons well. In the case of the neutral B mesons, there is agreement between data and Monte Carlo, although the statistical error on the data is large. These figures are

Sample	Dilution (%)	Eff. (%)	εD^2 (%)
	B^+		
Data	33 ± 8	36 ± 2	4.0 ± 1.9
MC with B^{**}	42 ± 1	29.0 ± 0.2	5.2 ± 0.2
MC w/o B^{**}	37 ± 1	26.9 ± 0.3	3.6 ± 0.2
	Uncorrected B^0		
Data	10 ± 10	41 ± 3	0.4 ± 0.9
MC with B^{**}	13 ± 2	27.1 ± 0.4	0.4 ± 0.1
MC w/o B^{**}	12 ± 2	26.5 ± 0.5	0.4 ± 0.1
	Corrected B^0		
Data	$19{\pm}19{\pm}2$	$41{\pm}3$	$1.5{\pm}3.0{\pm}0.3$
MC with B^{**}	$25{\pm}4{\pm}2$	$27.1{\pm}0.4$	$1.7{\pm}0.5{\pm}0.3$
MC w/o B^{**}	$23{\pm}4{\pm}2$	$26.5{\pm}0.5$	$1.4{\pm}0.5{\pm}0.3$

Table 2: Compilation of the results for dilution, efficiency, and εD^2 for charged and neutral B mesons including a comparison to Monte Carlo.

consistent with the ones extracted from the partially reconstructed B mesons in the previous section.

5 Conclusion

We have studied same side tagging in $p\bar{p}$ collisions at 1.8 TeV using the CDF detector at Fermilab. B mesons have been reconstructed in two ways.

Firstly, we use samples of partially reconstructed B mesons using the semileptonic decays $B^0 \to \ell^+ D^{(*)-} X$ and $B^+ \to \ell^+ \bar{D}^0 X$. We select the track with the minimum p_t^{rel} with respect to the momentum sum of that track, and the B candidate. We measure

$$\varepsilon D_+^2 = (5.7 \pm 1.5_{stat} \{^{+2.0}_{-1.2}\}_{syst})\% \text{ and } \varepsilon D_0^2 = (3.4 \pm 1.0_{stat} \{^{+1.2}_{-0.9}\}_{syst})\%.$$

This establishes same-side tagging for the first time in hadronic collisions. The measurement of the charged-track B-meson asymmetry as a function of proper time for neutral B mesons results in the observation of a time-dependent oscillation $B^0 \to \bar{B}^0$. We obtain $\Delta m_d = 0.446 \pm 0.057_{stat} + \{^{+0.034}_{-0.031}\}_{syst}$.

We confirm the power of the SST to tag the flavor of B mesons at production time by considering a sample of fully reconstructed B mesons, using the decays $B^0 \to J/\psi K^{*0}$ and $B^+ \to J/\psi K^+$. This sample has low combinatoric background, and, due to the identification of all the B decays products, the latter cannot be used in the tag by mistake. With a jet charge type of tagging algorithm we determine the effective tagging efficiencies for charge and neutral B mesons to be

$$\varepsilon D_+^2 = (4.0 \pm 1.9)\% \text{ and } \varepsilon D_0^2 = (1.5 \pm 3.0_{stat} \pm 0.3_{syst})\%.$$

The result for the fully reconstructed B^0 mesons, while statistics limited, is consistent with the one from the partially reconstructed B mesons.

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